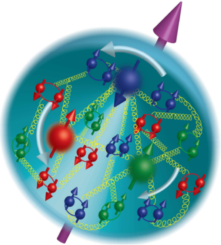
Introduction to spin physics, part II



Barbara Badełek
University of Warsaw

EIC PL Seminar

Warsaw, 25 I 2021

I thank the following colleagues:

M. Anselmino (DIS2019, Bad Honnef, 2017)
A. Bacchetta (Baryon2013, DIS2017, DIS2019)
F. Bradamante (IWHSS2019)
M. Contalbrigo (IWHSS2020)
J. Rojo (DIS2019)

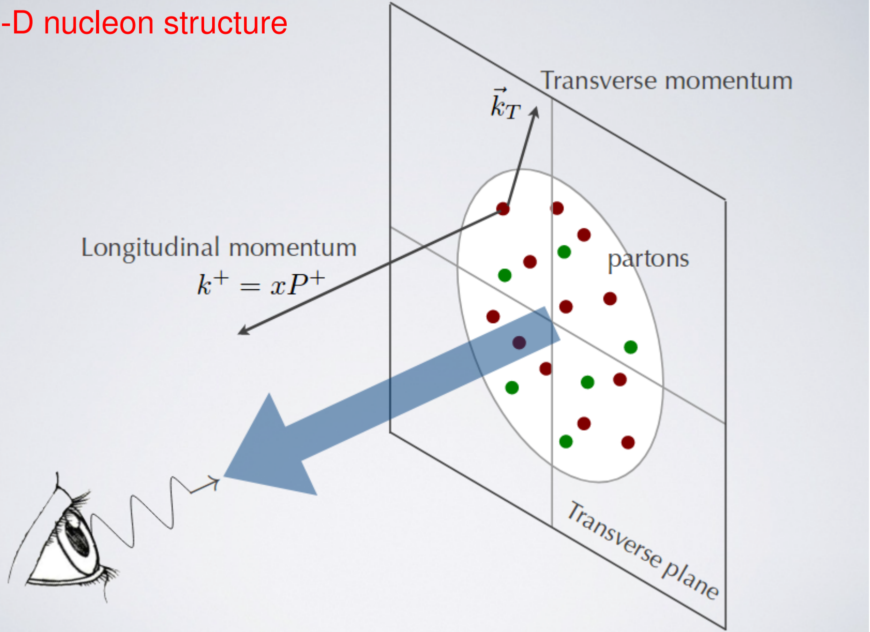
and others...

whose slides I used or followed.

There are more dimensions to explore, e.g. 3-D!

chiefly due to failures of the 1-D picture

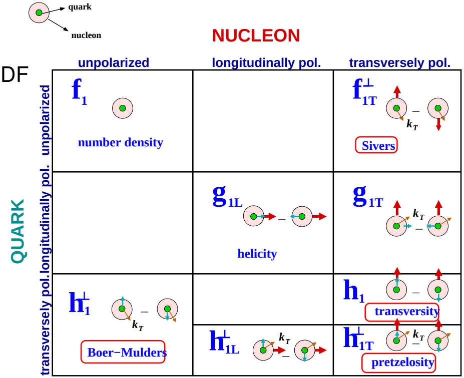
3-D nucleon structure



11 A. Bacchetta

Partonic structure of the nucleon; distribution functions

- In LT and considering k_{T},
  8 PDF describe the nucleon
  $\Longrightarrow$ Transverse Momentum Dependent PDF
- QCD-TMD approach valid $k_{\mathrm{T}} \ll \sqrt{Q^2}$
- After integrating over k_{T}
  only 3 survive: f_1, g_1, h_1
- TMD accessed in SIDIS and DY
  by measuring azimuthal asymmetries
  with different angular modulations
- SIDIS: e.g. $A_{\mathrm{Sivers}} \propto$ PDF $\otimes$FF
- DY: e.g. $A_{\mathrm{Sivers}} \propto$ PDF$^{\mathrm{beam}} \otimes$ PDF$^{\mathrm{target}}$

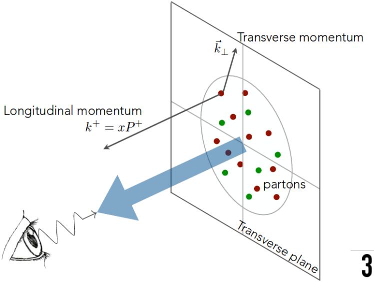


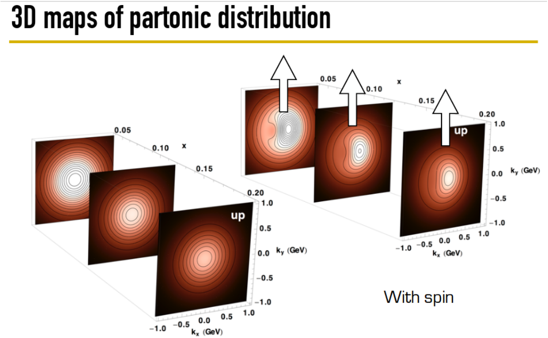
- OBS! Boer-Mulders and Sivers PDF are T-odd, i.e. process dependent

$$h_1^{\perp}(\mathrm{SIDIS}) = -h_1^{\perp}(\mathrm{DY}) \qquad\qquad f_{1\mathrm{T}}^{\perp}(\mathrm{SIDIS}) = -f_{1\mathrm{T}}^{\perp}(\mathrm{DY})$$

- OBS! transversity PDF is chiral-odd; may only be measured with another chiral-odd partner, e.g. fragmentation function.
- TMD parton distributions need TMD Fragmentation Functions!

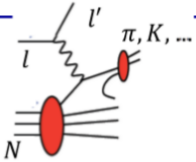
What does Sivers effect do?





A. Bacchetta, DIS2017

Semi-Inclusive Deep Inelastic Scattering

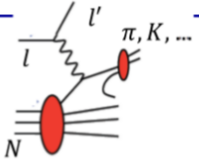


$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
&\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&\quad+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&\quad+S_\parallel\Big[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big]+S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big] \\
&\quad+|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) \\
&\qquad+\varepsilon\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\qquad+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] \\
&\quad+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
&\qquad+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},
\end{aligned}
$$

IWHSS19, Aveiro, 24 June 2019

F. Bradamante

Semi-Inclusive Deep Inelastic Scattering



$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,\boxed{F_{UU}^{\cos\phi_h}}$$

$h_1^\perp \otimes H_1^\perp$

$$+\,\varepsilon\cos(2\phi_h)\,\boxed{F_{UU}^{\cos 2\phi_h}}+\lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,\boxed{F_{LU}^{\sin\phi_h}}$$

$h_{1L}^\perp \otimes H_1^\perp$

$$+\,S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,\boxed{F_{UL}^{\sin\phi_h}}+\varepsilon\sin(2\phi_h)\,\boxed{F_{UL}^{\sin 2\phi_h}}\right]+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,\boxed{F_{LL}^{\cos\phi_h}}\right]$$

$f_{1T}^\perp \otimes D_1$

$$+\,|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(\boxed{F_{UT,T}^{\sin(\phi_h-\phi_S)}}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$h_{1T}^\perp \otimes H_1^\perp$

$h_1 \otimes H_1^\perp$

$$+\,\varepsilon\,\sin(\phi_h+\phi_S)\,\boxed{F_{UT}^{\sin(\phi_h+\phi_S)}}+\varepsilon\,\sin(3\phi_h-\phi_S)\,\boxed{F_{UT}^{\sin(3\phi_h-\phi_S)}}$$

$$+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,\boxed{F_{UT}^{\sin\phi_S}}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,\boxed{F_{UT}^{\sin(2\phi_h-\phi_S)}}\Big]$$

14 independent azimuthal modulations

$$+\,|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,\boxed{F_{LT}^{\cos(\phi_h-\phi_S)}}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,\boxed{F_{LT}^{\cos\phi_S}}$$

$$+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,\boxed{F_{LT}^{\cos(2\phi_h-\phi_S)}}\Big]\Big\},$$

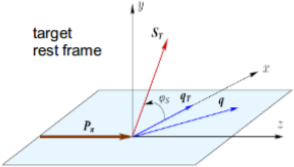
$g_{1T} \otimes D_1$

amplitudes of the modulations
→ TMD PDFs

IWHSS19, Aveiro, 24 June 2019

F. Bradamante

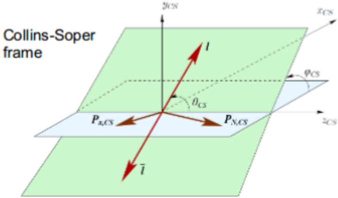
Drell-Yan cross-section



general expression

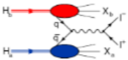
$$
\begin{aligned}
\frac{d\sigma}{dq^4 d\Omega} \propto \hat{\sigma}_U \Big\{ & 1 + \cos^2\theta_{CS}\, A_U^1 + \sin 2\theta_{CS}\; A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} + \sin^2\theta_{CS}\; A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\
& + S_T \Big[\Big(A_T^{\sin\varphi_S} + \cos^2\theta_{CS}\, \tilde{A}_T^{\sin\varphi_S} \Big) \sin\varphi_S \\
& + \sin 2\theta_{CS} \Big(A_T^{\sin(\varphi_{CS}+\varphi_S)} \sin(\varphi_{CS}+\varphi_S) + A_T^{\sin(\varphi_{CS}-\varphi_S)} \sin(\varphi_{CS}-\varphi_S) \Big) \\
& + \sin^2\theta_{CS} \Big(A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) + A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \Big) \Big] + \cdots \Big\}
\end{aligned}
$$

$\lambda = A_U^1, \mu = A_U^{\cos\varphi_{CS}}, \nu = 2\, A_U^{\cos 2\varphi_{CS}}$



IWHSS19, Aveiro, 24 June 2019

Drell-Yan cross-section



general expression $\pi^- p \to l^+ l^- X$

Boer-Mulders of the π — Boer-Mulders of the p

$$h_1^\perp \otimes h_1^\perp$$

$$\begin{aligned}\frac{d\sigma}{dq^4 d\Omega} \propto \hat{\sigma}_U \Big\{ & 1 + \cos^2\theta_{CS}\, A_U^1 + \sin 2\theta_{CS}\, A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} + \sin^2\theta_{CS} \boxed{A_U^{\cos 2\varphi_{CS}}} \cos 2\varphi_{CS} \\ & + S_T \Big[\Big(\boxed{A_T^{\sin\varphi_S}} + \cos^2\theta_{CS}\, \tilde{A}_T^{\sin\varphi_S} \Big) \sin\varphi_S \\ & + \sin 2\theta_{CS} \Big(A_T^{\sin(\varphi_{CS}+\varphi_S)} \sin(\varphi_{CS}+\varphi_S) + A_T^{\sin(\varphi_{CS}-\varphi_S)} \sin(\varphi_{CS}-\varphi_S) \Big) \\ & + \sin^2\theta_{CS} \Big(\boxed{A_T^{\sin(2\varphi_{CS}+\varphi_S)}} \sin(2\varphi_{CS}+\varphi_S) + \boxed{A_T^{\sin(2\varphi_{CS}-\varphi_S)}} \sin(2\varphi_{CS}-\varphi_S) \Big) \Big] + \cdots \Big\}\end{aligned}$$

$$f_1 \otimes f_{1T}^\perp$$

of the π — Sivers of the p

$$h_1^\perp \otimes h_1$$

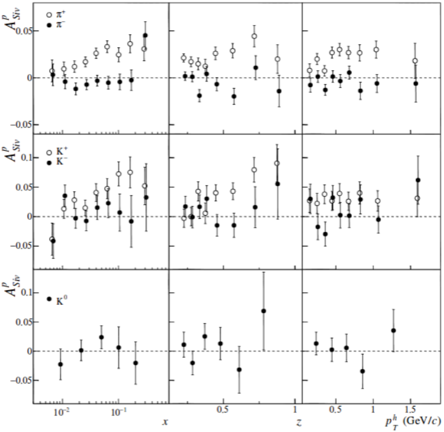
Boer-Mulders of the π — transversity of the p

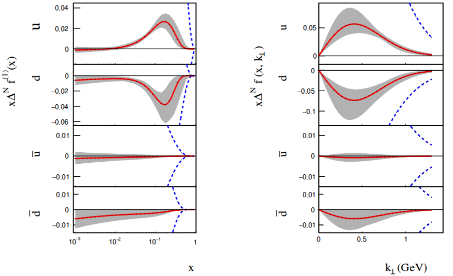
$$h_1^\perp \otimes h_{1T}^\perp$$

Boer-Mulders of the π — pretzelosity of the p

IWHSS19, Aveiro, 24 June 2019 — F. Bradamante

Results for the Sivers asymmetry for protons (SIDIS)



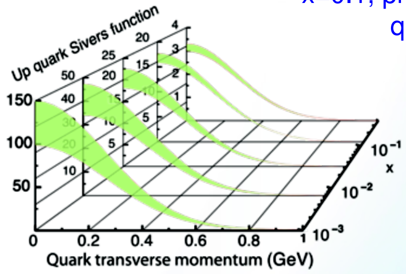


COMPASS, Phys.Lett. B744 (2015) 250

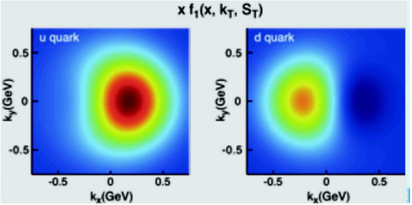
M.Anselmino et al.,JHEP 1704(2017)046

- Sivers asymmetries for proton measured for +/– identified hadrons are large for π^+, K^+...
- ...and even larger at smaller Q^2 (HERMES)
- COMPASS deuteron data show very small asymmetry

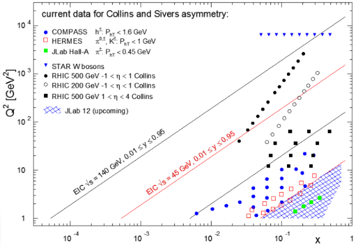
Sivers function at EIC



x=0.1, proton ⊥ polarised along y, moving along z
quark “flow” in a nucleon



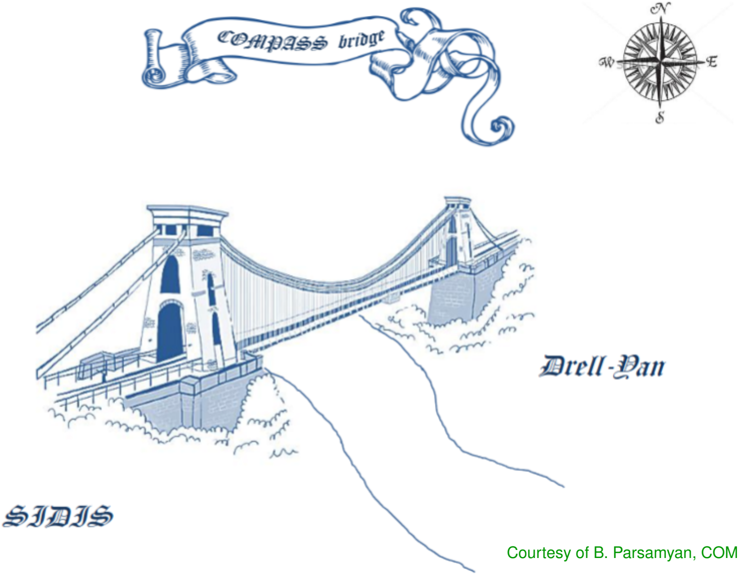
From “White paper”, arXiv:1212.1701



$\Longleftarrow$ EIC acceptance for Sivers meas.

O. Eyser, SPIN2016

The COMPASS bridge

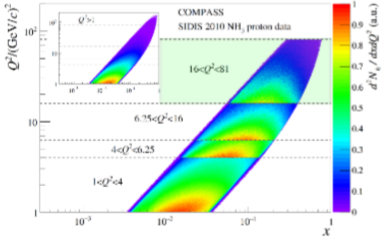


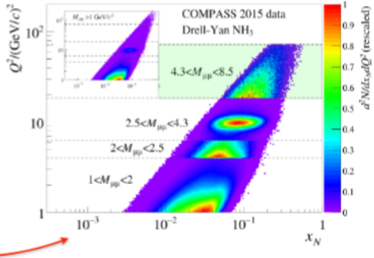
Courtesy of B. Parsamyan, COMPASS

COMPASS: SIDIS–DY bridge

$$\frac{d\sigma^{LO}}{dx\,dy\,dz\,dp_T^2\,d\varphi_h\,d\psi} \propto \left\{ \begin{array}{l} 1+\cos(2\phi_h)\varepsilon A_{UU}^{\cos(2\phi_h)} \\ + S_T \left[\begin{array}{l} \sin(\phi_h-\phi_S)A_{UT}^{\sin(\phi_h-\phi_s)} \\ +\sin(\phi_h+\phi_S)\varepsilon A_{UT}^{\sin(\phi_h+\phi_s)} \\ +\sin(3\phi_h-\phi_S)\varepsilon A_{UT}^{\sin(3\phi_h-\phi_s)} \end{array}\right] \end{array}\right\}$$

$$\frac{d\sigma^{LO}}{d\Omega\,d^4q} \propto \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta]}\cos(2\varphi_{CS})A_U^{\cos 2\varphi_{CS}} \\ + S_T\left[\begin{array}{l}\sin\varphi_S A_T^{\sin\varphi_S} \\ + D_{[\sin^2\theta]}\left(\begin{array}{l}\sin(2\varphi_{CS}+\varphi_S)A_T^{\sin(2\varphi_{CS}+\varphi_S)}\\ \sin(2\varphi_{CS}-\varphi_S)A_T^{\sin(2\varphi_{CS}-\varphi_S)}\end{array}\right)\end{array}\right] \end{array}\right\}$$





comparable x:Q^2 kinematic coverage

minimization of possible Q^2 evolution effects

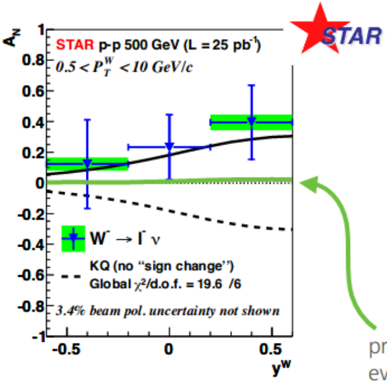
Unique experimental environment to test TMD universality and Sivers and Boer-Mulders sign change

29/08/2018 Riccardo Longo 9

SIVERS FUNCTION SIGN CHANGE

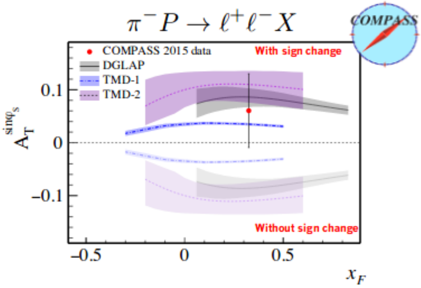
Sivers function SIDIS = – Sivers function Drell-Yan

Collins, PLB 536 (02)



STAR Collab. arXiv:1511.06003

prediction with TMD evolution equations

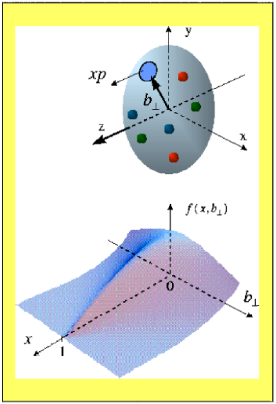


COMPASS PRL 119 (2017) 112002

A. Bacchetta, DIS2019

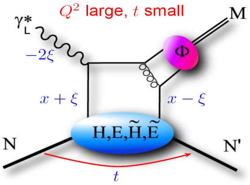
40

3-D proton
(in a different way $\Longrightarrow$ GPD)



After V.D. Volker, LANL 2007

Generalised Parton Distributions (GPD)



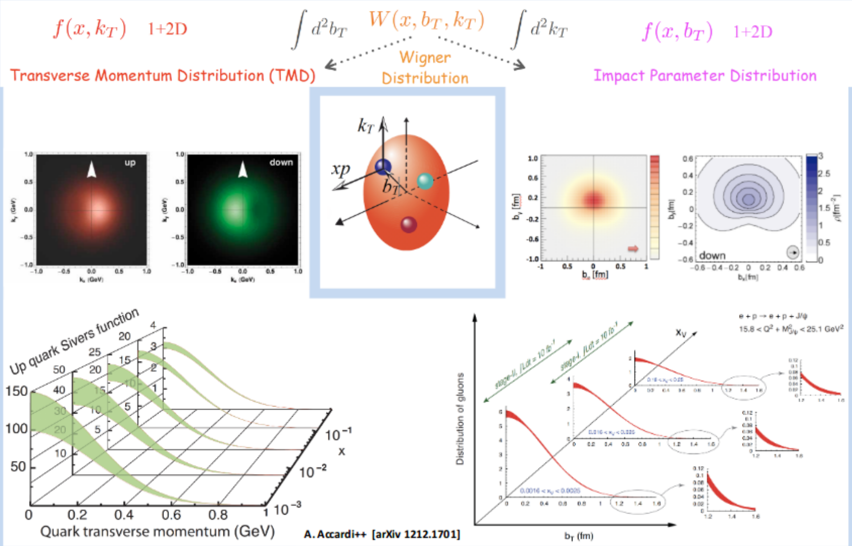
- Accessible via DVCS/DVMP: $\mu \mathrm{p} \to \mu \mathrm{p} \gamma(\mathrm{M})$
- 4 GDPs $(H, E, \widetilde{H}, \widetilde{E})$ for each flavour and for gluons

  plus 4 chiral odd ones $(H_T, E_T, \widetilde{H}_T, \widetilde{E}_T)$
- All depend on 4 variables: x, ξ, t, Q^2; DIS @ $\xi = t = 0$;
  Careful ! Here $x \neq x_{\mathrm{B}}$!
- $H, \widetilde{H}$ conserve nucleon helicity
  $E, \widetilde{E}$ flip nucleon helicity
- H, E refer to unpolarised distributions
  $\widetilde{H}, \widetilde{E}$ refer to polarised distributions
- $H^q(x, 0, 0) = q(x), \quad \widetilde{H}^q(x, 0, 0) = \Delta q(x)$

Important:

$$J_z^q = \frac{1}{2} \int dx \, x \, [H^q(x, \xi, t = 0) + E^q(x, \xi, t = 0)] = \frac{1}{2} \Delta\Sigma + L_z^q$$ (X. Ji)

3D Imaging

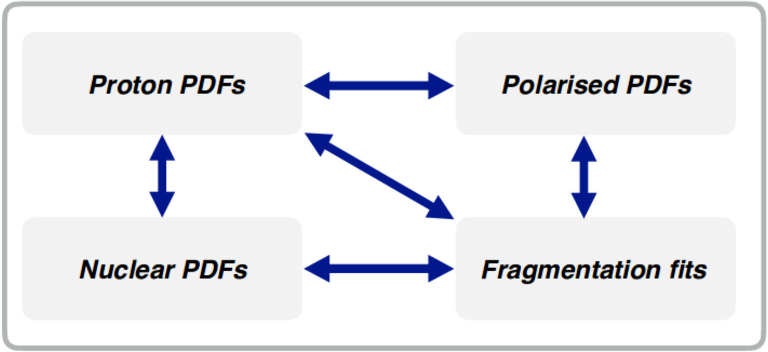


A. Accardi++ [arXiv 1212.1701]

Contalbrigo M. IWHSS 2020, 16th November 2020, ECSAC Trieste - Italy 17

Universal QCD fits

Pushing the **precision frontier** of **QCD fits** requires accounting for **cross-talk** between different **non-perturbative QCD** quantities



*Towards **universal/integrated global analyses** of non-perturbative QCD*

Juan Rojo 52 ***Proton Structure and PDFs***, **DIS2019**

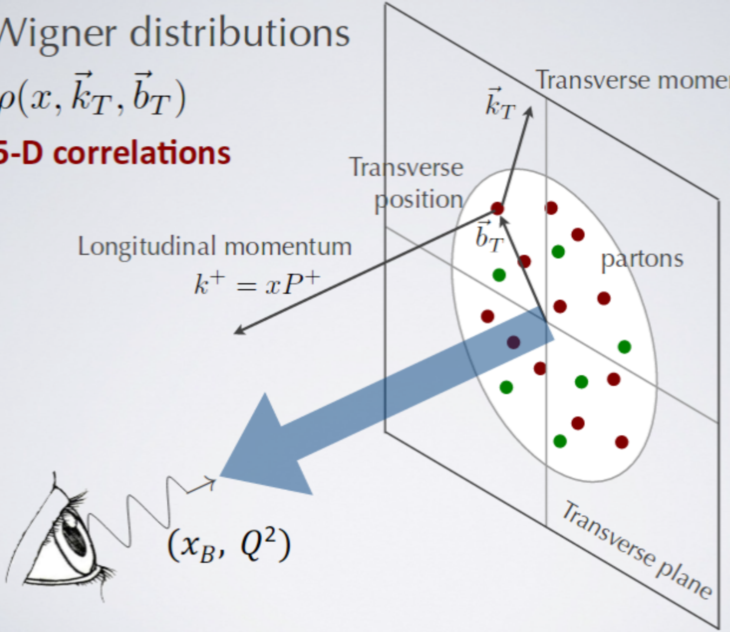
...Proton even 5-D!

(ultimate goal)

Wigner distributions

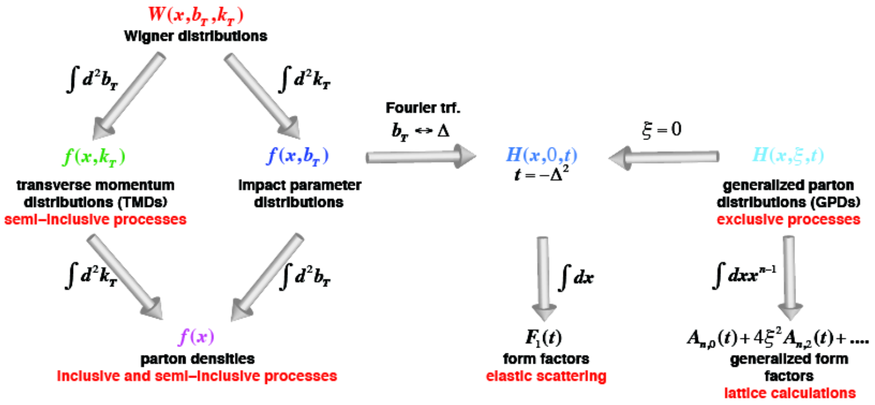
$\rho(x, \vec{k}_T, \vec{b}_T)$

5-D correlations



11 A. Bacchetta (Baryon 2013 Conference) *see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)*

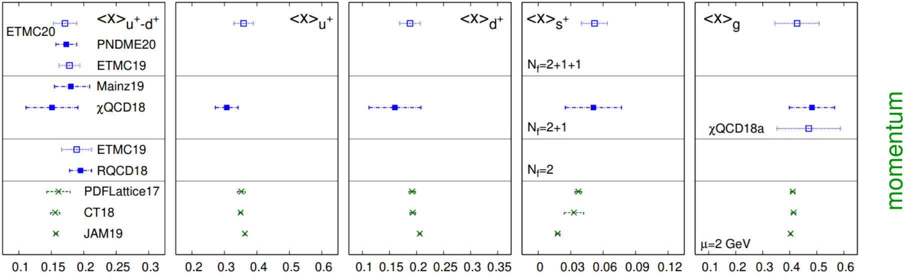
Descriptions of *pdf* ^{s} in the nucleon



From "White paper", arXiv:1212.1701

Any help from Lattice QCD ?

Lattice QCD developements (hep-ph 2006.08636v2)



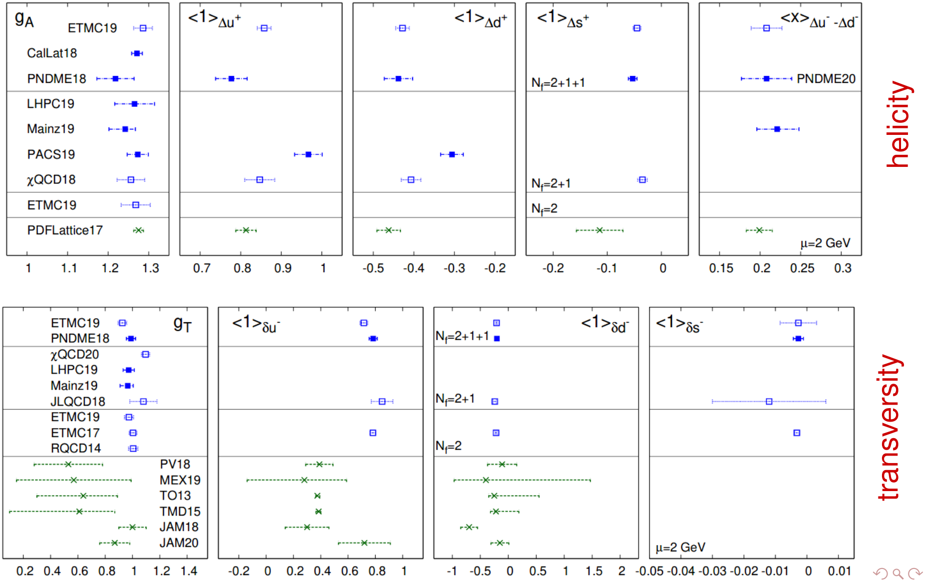
$$q^{\pm} \equiv q \pm \bar{q} \qquad \Delta q^{\pm} \equiv \Delta q \pm \Delta \bar{q}$$

n-th moments (momentum, helicity):

$$\langle x^n \rangle_{u^+-d^+}(Q^2) = \int_0^1 \mathrm{d}x\, x^n \left\{ u(x,Q^2) + \bar{u}(x,Q^2) - d(x,Q^2) - \bar{d}(x,Q^2) \right\}$$

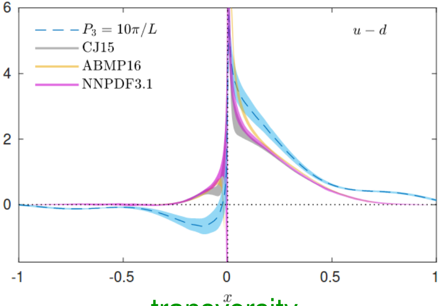
$$\langle x^n \rangle_{\Delta u^+-\Delta d^+}(Q^2) = \int_0^1 \mathrm{d}x\, x^n \left\{ \Delta u(x,Q^2) + \Delta\bar{u}(x,Q^2) - \Delta d(x,Q^2) - \Delta\bar{d}(x,Q^2) \right\}$$

Lattice QCD developements (hep-ph 2006.08636v2)

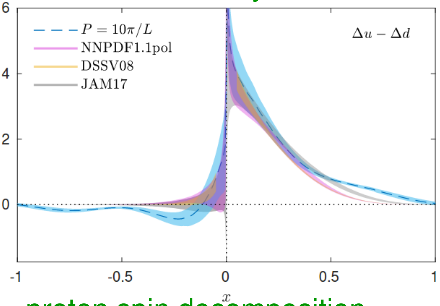


Lattice developements...cont'd (hep-lat 1902.00587v1)

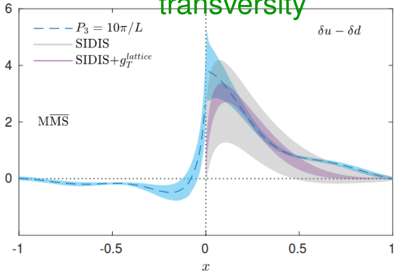
momentum



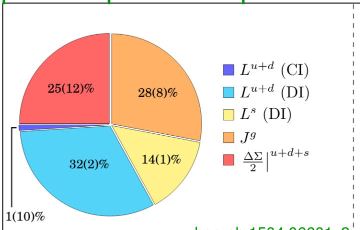
helicity



transversity



proton spin decomposition



hep-ph 1504.06601v2

Take-away menu

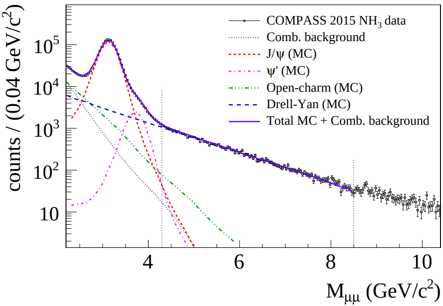
Proton structure very rich and developing quickly!

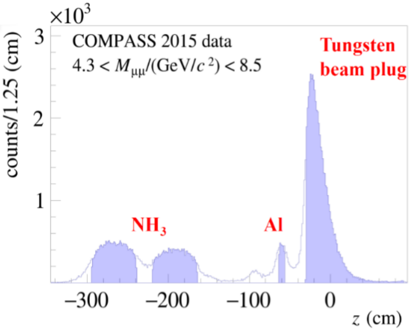
- 1-D proton momentum structure accurate and well controlled.
  Helicity and transversity (!) PDF need more effort.
- Experimental results suggest a necessity to go
  beyond the collinear parton picture of the nucleon.
- New promising concepts, which include spin (also as a tool):
  1. Transverse Momentum Dependent distributions, TMD
  2. Generalised Parton Distributions, GPD (not discussed).
- Data from: SIDIS, pp, Drell-Yan, e^+e^- (not discussed)
  $\Longrightarrow$ formulation of the 3-D imaging of the nucleon well advanced.
- Expected: new data from COMPASS, RHIC, LHCSpin, JLab at 12 GeV and the forthcoming Electron Ion Collider!
- Topical issue of EPJA dedicated to the 3-D nucleon structure:
  EPJ A52 (2016) no.6 (15 articles)!

SPARES

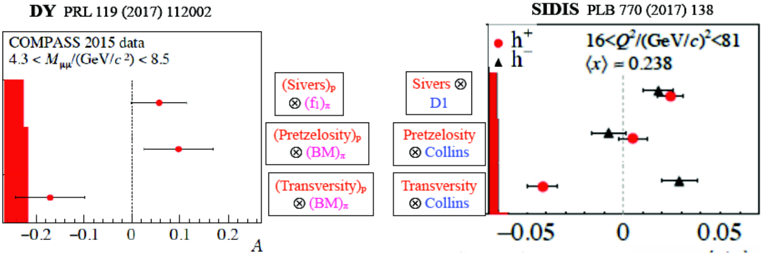
Drell-Yan process at COMPASS

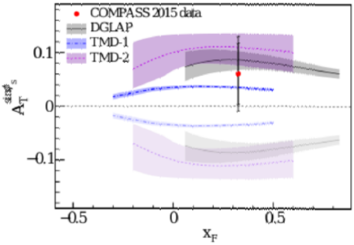
- $\pi^- + p \rightarrow \mu^+\mu^- + X$, beam: 190 GeV/$c$, target: $\perp$ polarised proton (NH_3)





COMPASS spin-dependent asymmetries in DY–SIDIS





In 2018

statistics ≈ 1.5 × 2015!

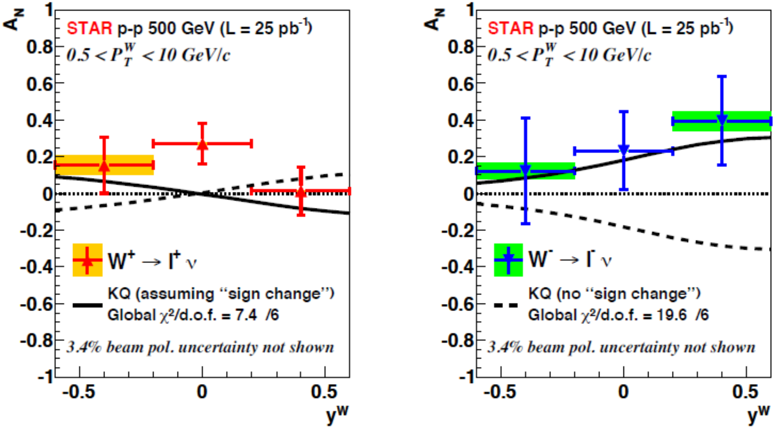
← sign change hypothesis

← NO sign change

PRL 119 (2017) 112002

First results from RHIC, $p^\uparrow p \to W^\pm X$

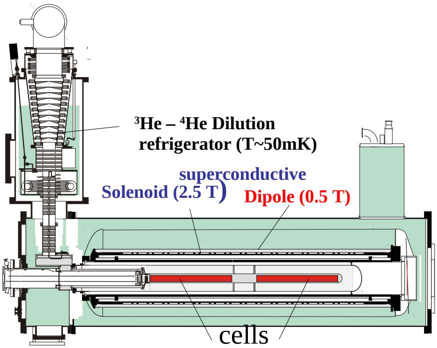
STAR Collaboration, PRL 116 (2016) 132301

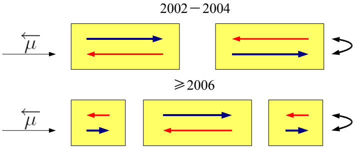


some hints at sign change of Sivers function.....

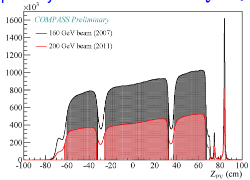
M. Anselmino, Bad Honnef 2017

COMPASS polarised targets: NH_3 and ^{6}LiD



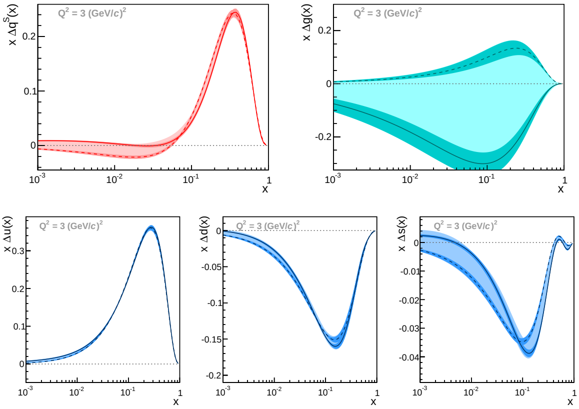


NH_3, primary vertex resolution at Q^2 <1 (GeV/c)^2



* Two (three) target cells, oppositely polarised
* Polarisation reversed every 8 h (less frequent after 2005) by field rotation
* Material: solid ^{6}LiD (NH_3)
* Polarisation: ~ 50% (~90%), by the Dynamical Nuclear Polarisation
* Dilution: f~0.4 (~0.15)
* Polar acceptance: ~70 mrad (~180 mrad after 2005)

NLO QCD fit: results for g_1^{p}, g_1^{d}, $g_1^{^3He}$ inclusive data, $W^2 > 10\ (\mathrm{GeV}/c^2)^2$



PLB 753 (2016) 18

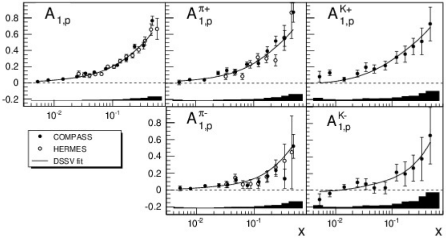
- Statistical uncertainties (dark bands) $\ll$ systematic (light bands)
- Gluon polarisation poorly constraint $\Longrightarrow$ “direct” methods
- Quark spin contribution to the nucleon spin: 0.26 $< \Delta\Sigma <$0.36 (due to poor Δg)

Semi-inclusive asymmetries and parton distributions

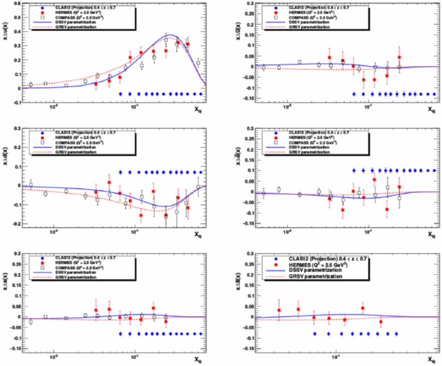
- COMPASS: measured on both proton and deuteron targets
for identified, positive and negative pions and (for the first time) kaons

COMPASS, Phys. Lett. B **693** (2010) 227

DSSV, Phys. Rev. D **80** (2009) 034030



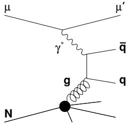
CLAS12, Update to E12-09-007

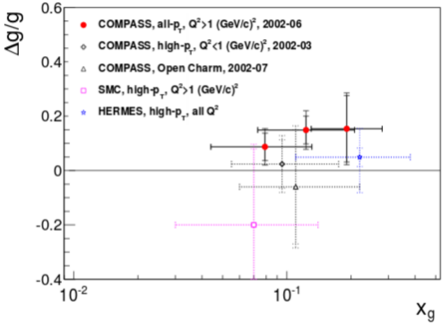


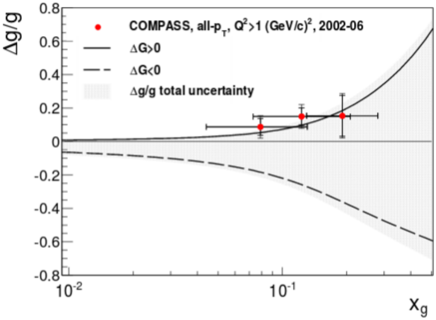
- COMPASS: LO DSS fragm. functions and LO unpolarised MRST assumed here.
- NLO parameterisation of DSSV describes the data well.

Direct measurements of $\Delta g(x)$

Direct measurements – *via* the cross section asymmetry for the photon–gluon fusion (PGF) with subsequent fragmentation into $c\bar{c}$ (LO, NLO) or $q\bar{q}$ (high $p_{\rm T}$ hadron pair (LO)): $A_{\gamma \rm N}^{\rm PGF} \approx \langle a_{\rm LL}^{\rm PGF} \rangle \dfrac{\Delta g}{g}$







COMPASS from SIDIS on d for any $(p_{\rm T})_{\rm h}$ and at LO:

$$\Delta g/g = 0.113 \pm 0.038(\text{stat.}) \pm 0.036(\text{syst.}) \quad \text{at} \quad \langle Q^2 \rangle \approx 3\ (\text{GeV}/c)^2, \quad \langle x_g \rangle \approx 0.10$$

clearly positive gluon polarisation!

COMPASS, EPJC 77(2017) 209

Supersymmetry

- Expected symmetry; transforms

$$\text{fermions} \leftrightarrows \text{bosons}$$

- For fermions – Pauli principle; for bosons – no!
- Partners of all known particles expected:

particle	spin ($\hbar$)	sparticle	spin ($\hbar$)
q	1/2	squark, $\tilde{q}$	0
l	1/2	slepton, $\tilde{l}$	0
γ	1	fotino, $\tilde{\gamma}$	1/2
g	1	gluino, $\tilde{g}$	1/2
W, Z	1	vino, $\tilde{W}$; zino, $\tilde{Z}$	1/2
H	0	higgsino, $\tilde{H}$	1/2
G	2	gravitino, $\tilde{G}$	3/2

- Of course it is broken.
- Makes a framework for unification of all interactions.